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THE ACCRETION GEOMETRY IN RADIO-LOUD ACTIVE GALAXIES

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We review the latest attempts to determine the accretion geometry in radio-loud active galactic nuclei (AGN). These objects, which comprise $\sim 10\text{--}20\%$ of the AGN population, produce powerful collimated radio jets that can extend thousands of parsecs from the center of the host galaxy. Recent multiwavelength surveys have shown that radio-loudness is more common in low-luminosity AGN than in higher luminosity Seyfert galaxies or quasars. These low-luminosity AGN have small enough accretion rates that they are most likely accreting via a geometrically thick and radiatively inefficient accretion flow. In contrast, X-ray spectroscopic observations of three higher luminosity broad-line radio galaxies (3C 120, 4C+74.26 and PG 1425+267) have found evidence for an untruncated thin disk extending very close to the black hole. These tentative detections indicate that, for this class of radio-loud AGN, the accretion geometry is very similar to their radio-quiet counterparts. These observations suggest that there are three conditions to jet formation that must be satisfied: the presence of a rapidly spinning black hole, an accretion flow with a large H/r ratio, and a favorable magnetic field geometry.

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1. Introduction

As gas and dust accretes onto a supermassive black hole at the center of a galaxy, a significant amount of gravitational potential energy is liberated. In a radiatively efficient accretion flow, one-half of this energy is radiated away to infinity,¹ allowing these active galactic nuclei (AGN) to be observed out to vast cosmological distances.^{2,3} However, there are other avenues through which the accretion energy can be released, such as the driving of outflows or large scale motions of the accretion flow.^{4,5} These processes do not produce strong observable signatures, so observations simply detect a drop in the radiative efficiency of the accretion flow.

Three decades ago, radio observations of AGN uncovered another pathway for energy release by accreting black holes: highly collimated jets of relativistic plasma extending thousands of parsecs from the center of the galaxy.^{6,7,8} Only $\sim 10\text{--}20\%$

of AGN fall into this ‘radio-loud’ category,^{9,10} and, despite years of study, the exact mechanism that produces this spectacular release of energy is still unknown. As these jets are produced at the centers of active galaxies, it is natural to ask if there is a difference in the accretion flow between the radio-loud and radio-quiet populations. This short review summarizes the attempts made over the last several years to answer this question. We begin in the next section by collecting some of the key observational properties and correlations of radio-loud AGN, including the various definitions of what constitutes a radio-loud AGN. With the explosion in large-scale and multi-wavelength surveys over the last decade, more information than ever is available on the properties of radio-loud AGN and their host galaxies. Section 3 then presents the results of measurements of the accretion geometry of radio-loud AGN and compares them to the non-jet producing AGN. Finally, in the last section, we collect together all the various data and models and try to answer the question: how do black holes make jets?

2. Definition of a Radio-Loud AGN

All AGN emit at radio wavelengths at some level (i.e., there are no ‘radio-silent’ sources), so the radio power must be compared to the emission at higher frequencies to determine the ‘radio-loudness’ of a given object. Early radio surveys of optically selected quasars measured the radio-loudness as the ratio between the monochromatic luminosities at 5 GHz and 4400 Å, $R = \nu L_{5 \text{ GHz}} / \nu L_{4400 \text{ Å}}$.^{9,11,12,13} These studies found that the distribution of quasars was roughly bimodal, with the vast majority of objects found to be radio-quiet (i.e., $R \lesssim 10$). An alternative definition of R is a comparison between the radio and X-ray luminosity, $R_X = \nu L_{5 \text{ GHz}} / \nu L_{2-10 \text{ keV}}$.¹⁴ The advantage of this definition is that the hard X-ray band is less sensitive to extinction and is closely related to the accretion power. In this case, the dividing line between the radio-loud and radio-quiet population is $\log R_X = -4.8$.

This relatively simple view of the so-called radio-loud/radio-quiet dichotomy has been made significantly more complex with the advent of deep, multi-wavelength, and wide-field imaging surveys. For example, it is no longer clear that R is bimodal, since many radio-selected quasars fall between the original radio-loud and radio-quiet definitions.^{15,16,17} However, other selection techniques and surveys continue to show evidence for a bimodality.¹⁰ A recent study using the Sloan Digital Sky Survey indicates that, after years of conflicting results,^{11,23,24} the fraction of quasars that are radio-loud decreases with increasing redshift and with decreasing luminosity.²⁵ The new large surveys have also shown that if one uses the fixed values of R or R_X as a dividing line, the fraction of radio-loud AGN *increases* with *decreasing* Eddington ratio.^{18,19,20,21} A recent large and heterogeneous sample compiled by Sikora et al. shows that there exists both a radio-loud and a radio-quiet sequence at all accretion rates (see the left-hand panel of Figure 1).²² These results illustrate the limitation of using R or R_X in determining whether an AGN

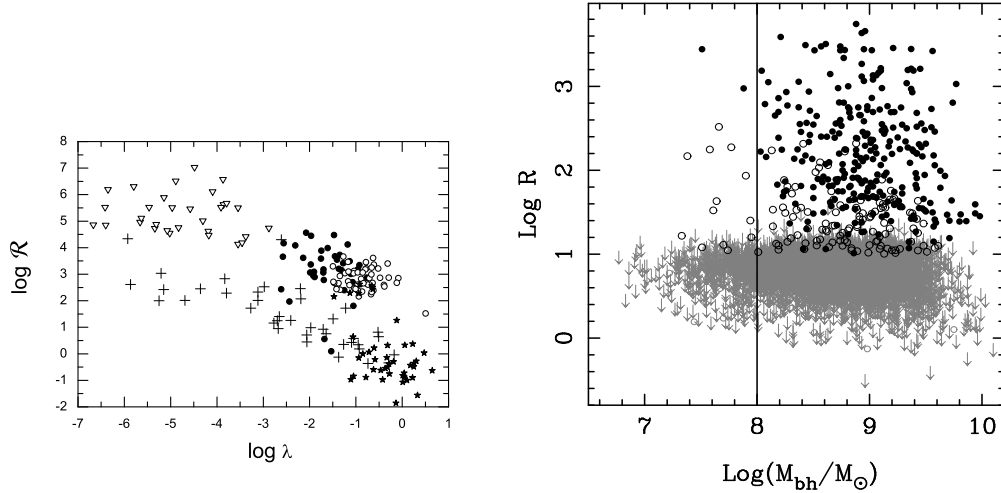


Fig. 1. (Left) Plot of the radio-loudness parameter R as a function of the Eddington ratio $\lambda \equiv L_{\text{bol}}/L_{\text{Edd}}$. The different symbols denote different types of AGN: filled circles \rightarrow broad-line radio galaxies, open circles \rightarrow radio-loud quasars, crosses \rightarrow Seyfert galaxies and LINERs, open triangles \rightarrow FR I radio galaxies and filled stars \rightarrow PG quasars. Plot taken from Ref. 22. (Right) As in the other panel, but now plotting R against black hole mass for quasars selected from the Sloan Digital Sky Survey. Black points denote the radio-loud quasars, while the gray symbols are the radio-quiet objects. Figure taken from Ref. 31.

is radio-loud or radio-quiet, since not all of these radio-loud low-luminosity AGN produce powerful jets, the subject of this review. For example, Sgr A* and M87 both have very similar values of R showing them to be extremely radio-loud, yet only M87 produces a powerful radio jet. The observed increase in radio-loudness with decreasing Eddington ratio may indicate a change in how accretion energy is directed and liberated around black holes.

The last decade has also seen a massive increase in our understanding of the host galaxies of both radio-loud and radio-quiet AGN, most notably with the use of the radius-luminosity relation derived from reverberation mapping to weigh the central supermassive black hole.^{26,27,28} Various studies have concluded that while the black hole at the heart of radio-quiet AGN can have a wide range of masses, radio-loud AGN almost always have central black holes with masses $> 10^8 M_{\odot}$ (see the right-hand panel of Figure 1),^{29,30,31,32} although there are dissenting views.³³ This result is consistent with earlier work that showed that radio-loud AGN seem to be almost exclusively hosted by early type galaxies (i.e., galaxies with massive bulges).³⁴ Radio-quiet AGN can reside in either spiral or elliptical galaxies.^{35,36,37} Now, *HST* observations of low-luminosity AGN in early type hosts have shown that the radio-loud sources have bulges with central cores in their brightness profiles, while the radio-quiet ones have power-law brightness profiles.^{38,39} Central cores may be formed through dynamical effects following a merger with another massive galaxy.^{40,41}

Although these observational advances are impressive, they are still limited by the difficulty in selecting an unbiased and complete sample of objects. This is especially difficult for AGN, where the vast majority suffer some level of obscuration,^{42,43} but is doubly problematic for radio-loud objects, as these sources are relatively scarce within the overall population. Therefore, it is important for the above observational results to be confirmed and clarified with a proper understanding of the biases involved in selecting the galaxy samples.

3. Determining the Accretion Geometry

As accretion flows in external galaxies cannot be resolved by imaging, indirect methods such as hard X-ray spectroscopy are required to probe the structure of the accretion disk. The variability properties of hard X-rays from AGN shows that they are produced within the innermost regions of the accreting material. Hard X-ray spectra of bright AGN obtained by the *Ginga* and *ASCA* observatories showed that the underlying X-ray power-law hardens at $\gtrsim 8$ keV and often features a Fe $K\alpha$ fluorescent line at 6.4 keV.^{44,45} These features are most naturally interpreted as evidence of reprocessing (or reflection) of the X-ray power-law in dense, relatively cold material lying out of the line of sight.^{46,47,48} Deep observations of bright Seyfert 1 galaxies such as MCG-6-30-15 showed that the Fe $K\alpha$ line could be highly asymmetric and exhibit a broad red wing.^{49,50,51} These features match those predicted by models of X-ray illuminated accretion disks where relativistic effects sculpt the Fe $K\alpha$ line into a characteristic shape.^{52,53,54} Fitting these models to the observed X-ray spectra showed that the line emission must be being produced well within $10 r_g$ (where $r_g \equiv GM/c^2$ is the gravitational radius of a black hole with mass M).⁵⁵ Thus, the reflection features observed in the hard X-ray spectra of AGN could provide information on the extent, ionization state,⁵⁶ composition,⁵⁷ and structure of the accretion disk very close to the black hole.^{58,59,60}

Unfortunately, such studies have been difficult to apply to radio-loud AGN. First, as mentioned above, radio-loud AGN are relatively scarce so there exists very few sources that have a high 2–10 keV flux. A precise measurement of a Fe $K\alpha$ line profile requires a careful understanding of the underlying continuum and thus a high signal-to-noise spectrum. As a result, very few radio-loud AGN are bright enough in the X-ray band to provide the high quality data necessary for detailed spectral analysis without very long exposure times. A second problem arises from the presence of the radio jet itself. The relativistic plasma in the jet can produce X-rays via synchrotron, synchrotron self-Compton or by Compton up-scattering of low energy photons from the accretion disk. Thus, depending on the viewing angle into the central engine and the jet dynamics, any accretion disk reflection features may be hidden or altered by X-rays produced by the jet.^{61,62,63}

Despite these problems, X-ray observations of a significant number of radio-loud AGN were performed in the 1990s with *ASCA*, *RXTE* and *BeppoSAX*.^{64,65,66,67} The best evidence for reflection features and Fe $K\alpha$ lines were found in broad-

line radio galaxies (BLRGs), radio-loud AGN whose optical spectra show similar broad permitted lines as radio-quiet type 1 AGN. Considering the results on BLRGs collectively it was found that they have harder X-ray power-laws, weaker reflection strengths and smaller Fe $K\alpha$ equivalent widths than their radio-quiet Seyfert 1 counterparts.⁶² There was no clear detection of a relativistically broadened Fe $K\alpha$ line from the inner disk of a BLRG. This result was interpreted as a change in accretion geometry between the two classes. Specifically, the dense, geometrically thin inner accretion disk in the radio-quiet AGN was replaced in BLRGs with a tenuous, geometrically thick flow (such as an Advection Dominated Accretion Flow; see Ref. 68) that would not produce strong reflection features. Alternatively, the weak reflection features in BLRGs may also be evidence of a highly ionized untruncated accretion flow.⁶⁹ A third possibility is that the reflection features are being diluted by the radio jet, however a recent reanalysis of *BeppoSAX* data of three BLRGs has shown that any non-thermal jet component contributes $< 45\%$ of the flux in the 2–10 keV band.⁷⁰ Of course, it is difficult to rule out the possibility of jet dilution for every BLRG without the presence of very high energy data.

It was hoped that the substantial increase in sensitivity afforded by the *XMM-Newton* and *Chandra* observatories would allow for a clearer picture of the accretion geometry within radio-loud AGN. Unfortunately, in many cases the results have remained frustratingly ambiguous. The BLRGs NGC 6251, 3C 109 and 3C 111 all show evidence of reflection and a broad Fe $K\alpha$ line,^{71,72,73} but the data quality was still not high enough to tightly constrain the continuum and line models. Thus, no strong conclusions could be made about the properties of the inner accretion disk. Firmer results were obtained following a 127-ks *XMM-Newton* observation of 3C 120, the brightest BLRG in the X-ray sky. These data showed a resolved Fe $K\alpha$ line with an equivalent width of ~ 50 eV. The line, however, was clearly narrow with the innermost radius being $\gtrsim 75 r_g$ at an inclination angle of 10° .^{74,75} This result seemed to indicate a truncated accretion disk in 3C 120, although the presence of a highly ionized inner disk could not be ruled out.⁷⁴ However, a very recent observation of 3C 120 by *Suzaku* does show evidence of a weak (equivalent width ~ 32 eV) broad Fe $K\alpha$ line with an inner radius of $\sim 10 r_g$, indicating the presence of an untruncated optically thick disk.⁷⁶ Interestingly, the equivalent width of this line is smaller than the upper limit of any broad component in a recent simultaneous *Chandra-RXTE* observation of 3C 382 that was unable to detect a broad Fe $K\alpha$ line.⁷⁷ This result indicates that very long observations may be necessary in order to detect the broad components of Fe $K\alpha$ lines in radio-loud AGN.

Aside from the recent *Suzaku* observation of 3C 120, there have been two other indications of relativistically broadened Fe $K\alpha$ lines in BLRGs. Figure 2 shows the line profiles determined from *XMM-Newton* observations of two broad-line quasars, 4C+74.26 and PG 1425+267. After taking into account the narrow line core at 6.4 keV, both objects show evidence for a remaining relativistically broadened component.^{78,79} In the case of PG 1425+267, the data were not able to precisely

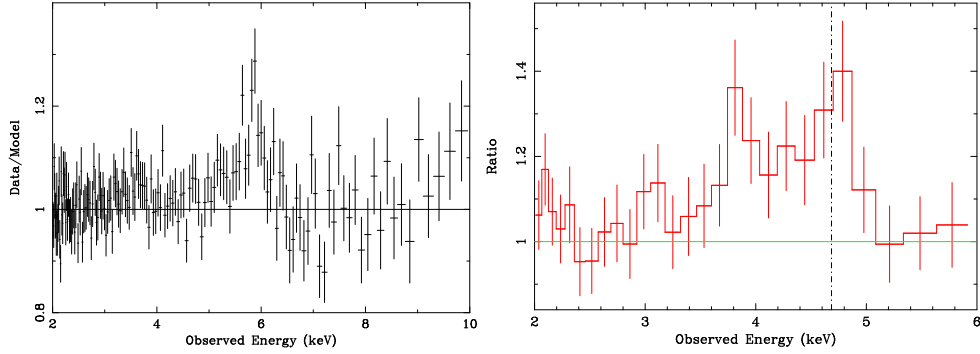


Fig. 2. (Left) The line profile obtained from a *XMM-Newton* observation of 4C+74.26. The core of the line is well fit by narrow Fe K α line, with a weak broad component extending to lower energies. The relativistic line must originate with $10 r_g$ and the inner radius is within $6 r_g$. Plot taken from Ref. 78. (Right) As in the other panel, but now showing the line profile from PG 1425+267. The vertical line indicates the rest-frame energy of the neutral Fe K α line at 6.4 keV. After fitting the narrow line core, the remaining broad emission is consistent with a relativistic line from the inner disk. Figure taken from Ref. 79.

determine the emission radii, but the line is consistent with emission down to $6 r_g$, the innermost stable circular orbit (ISCO) of a Schwarzschild (i.e., non-spinning) black hole, although the authors were unable to rule out emission from within this radius.⁷⁹ In contrast, the inner radius of the broad line in 4C+74.26 could be fit with a value close to the ISCO for a maximally spinning Kerr black hole.⁷⁸ In fact, the outer radius was also found to lie within $10 r_g$. The reflection continuum was consistent with arising from a moderately ionized medium. The broadness of these lines and the complexity of the underlying continua argues for a consistent campaign of long observations to confirm the presence and extent of these detections.

An alternative, yet highly model dependent, method of probing accretion geometry in radio-loud AGN is through comparison of spectral energy distributions with accretion disk models. When the accretion rate of an AGN is less than $\sim 1\%$ of its Eddington limit the flow geometry can transition to an optically-thin, radiatively inefficient flow that is not expected to provide strong reflection features.⁸⁰ With the advent of simple methods to estimate the mass of the central black hole in AGN, it is now possible to determine the Eddington ratio of large samples of AGN, modulo uncertainties in the black hole mass and bolometric correction. X-ray studies of low-luminosity radio-loud AGN with very low Eddington ratios suffer from difficulty in isolating the nuclear continuum from other sources in the galaxy that may be equally bright. High-resolution imaging by *Chandra* mitigates this problem and all observations of such low-luminosity radio galaxies have found no evidence for reflection from an inner accretion disk.^{21,81} This supports the hypothesis that these weakly accreting objects host radiatively inefficient accretion flows (although see Ref. 82). In contrast, the three AGN with possible relativistic reflection features in their X-ray spectra (3C 120, 4C+74.26 and PG 1425+267) all have Eddington ratios

$\gtrsim 0.05$, consistent with the idea that these objects are unlikely to have radiatively inefficient accretion flows close to the black hole.

In summary, the accretion geometry of radio-loud AGN seems to depend on the accretion rate. The majority of the radio-loud AGN population may lie at low accretion rates, where it is expected that there is an optically-thin, geometrically thick accretion flow close to the black hole. However, a small fraction of more rapidly accreting AGN also are radio-loud and indications from relativistically broadened Fe K α lines show that these sources have ‘normal’ geometrically thin, optically thick disks down to very small radii. The X-ray spectral observations are very difficult as the sources are typically faint and very long exposure times are required to provide the necessary data. Such observations have been very difficult to come by and the three detections of relativistically broadened Fe K α lines in BLRGs are therefore still tentative. It is imperative, therefore, that a campaign of long (200+ ks) observations with *XMM-Newton* or *Suzaku* be performed on all nearby BLRGs to provide more definitive results on the accretion geometry in radio-loud AGN.

4. How do Black Holes Make Jets?

Given the relative scarcity of radio-loud AGN, it must be very difficult for accreting black holes to produce powerful collimated jets. This fact then implies that the jet production mechanism must depend on a number of different parameters or conditions, each of which must be fulfilled in order to launch a highly relativistic jet. In this section we collect together many of the observational results of the last few years, and, in combination with recent theoretical work, discuss those parameters that are likely to be important for jet formation. The X-ray spectroscopic results described in the previous section will also be taken at face value, although we again emphasize the need for long follow-up observations to confirm the broad Fe K α line detections.

4.1. Black Hole Spin

Black holes may possess an angular momentum J that is often conveniently written in dimensionless form $a = J/J_{\text{max}} = cJ/GM^2$. In 1977 Blandford and Znajek showed that the spin energy of black hole could be extracted given an electromagnetic connection between the hole and a nearby ‘load’.⁸³ The spin energy may then be the ultimate source for producing powerful radio jets. This can be seen by noting that the available energy that is potentially extractable from a maximally spinning hole would be enough to account for the luminosities of the most powerful radio-loud quasars.⁸⁴ Numerical simulations of accretion onto black holes seem to confirm this scenario, with the power of the numerical jet increasing significantly with the value of a .^{85,86}

Thus, a possible scenario for the origin of radio-loud AGN is that only those galaxies harbor rapidly spinning black holes, while the radio-quiet AGN host only

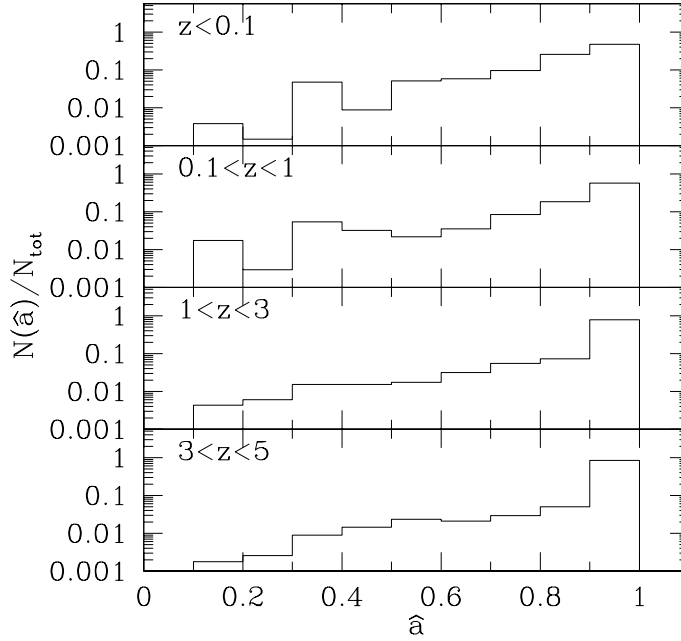


Fig. 3. The evolution of the distribution of black hole spins through both mergers and accretion. The vast majority of black holes end up with high values of a . Plot taken from Ref. 90.

weakly spinning or Schwarzschild black holes.^{22,87} This would imply that the majority of AGN (and therefore galaxies) would have weakly spinning black holes. The justification for this conclusion arises from calculations of black hole growth through mergers. Only massive black holes that have had a merging event with another massive object produce a rapidly spinning black hole.^{87,88} Indeed, since mergers can occur with any random impact parameter, a number of smaller mergers will not necessarily increase the spin of the resulting black hole.⁸⁸ Such a model is consistent with the observational result that radio-loud AGN almost exclusively reside in elliptical-like galaxies with core-like brightness profiles, which are most naturally formed following a major merger. However, black holes will also accrete a significant amount of gas following merger events, and this will almost always cause the black hole to spin up.⁸⁹ Figure 3 shows the results of a calculation performed by Volonteri et al. where they took into account both accretion and the effects of mergers over cosmological timescales.⁹⁰ They found that most black holes are already rapidly spinning by $z \sim 5$. A possible way to avoid such a rapid increase in a is if a galaxy suffers very few major mergers and accretes only very small parcels of gas at random angles.⁹¹ In this case, it is possible for counter-aligned accretion to drive down the angular momentum of the black hole. Such a scenario would lead to

radio-quiet AGN residing primarily in disk galaxies as is observed; however, more work is required to show that this rather confining scenario is a natural outcome of galaxy evolution.

One other problem with the model of a pure spin dependence on jet launching arises from the comparison of the local black hole mass density to the accreted mass density of quasars.⁹² All measurements using the latest quasar luminosity functions find that, in order to match the accreted mass density to the local quiescent black hole mass density, the average radiative efficiency of quasars must be > 0.1 , higher than the maximum efficiency for a non-spinning black hole.^{93,94,95} This result implies that the vast majority of black holes in quasars (which are predominately radio-quiet) have rapidly spinning black holes.

Observationally, the only direct probe of the spin of a black hole is through relativistic broadened Fe K α lines. It is therefore interesting to consider the case of MCG-6-30-15. This local radio-quiet Seyfert 1 resides in an E-S0 galaxy and has a black hole mass estimate of $\sim 4 \times 10^6 M_{\odot}$.⁹⁶ Its X-ray spectrum shows a very broad Fe K α line that requires emission from within the ISCO of a Schwarzschild black hole.⁵⁰ In fact, a very careful spectral analysis performed by Brenneman and Reynolds derived a lower limit to the black hole spin of $a > 0.989$.⁹⁷ This is to be compared with the tentative detection of the broad Fe K α line in 4C+74.26, that also requires line emission from close to the ISCO of a rapidly spinning black hole.⁷⁸ Thus, here are two examples of rapidly spinning black holes in AGN, one being radio-loud and the other radio-quiet. Sikora et al. postulate that the example of MCG-6-30-15 (along with radio-quiet quasars) could be explained by the lack of any appropriate MHD collimation in the inner-region of the accretion flow.²² This is similar to arguments that radio-loud quasars may be equivalent to the flaring states of microquasars and therefore radio-loud quasars are only a short-lived phenomenon in the life of a quasar.⁹⁸

Finally, it is worth noting that Galactic black holes typically produce significant radio emission only in their low/hard states.⁹⁹ At higher accretion rates, in their high/soft state, the jet emission disappears.^{100,101} Spin estimates of Galactic black holes vary depending on the measurement technique, with broad Fe K α lines resulting in values of $a \gtrsim 0.9$,¹⁰² while comparisons of the accretion disk temperature and luminosity with spectral models yield $a \lesssim 0.8$.¹⁰³ The actual value of a is irrelevant however, as the spin of a Galactic black hole will not change when it transitions from the low/hard to the high/soft state. Thus, for the Galactic black holes there must be some other parameter in addition to black hole spin that is required to produce jetted radio emission.

All these results, both observational and theoretical, seem to suggest that the spin energy of a black hole is the ultimate energy source for powerful radio jets, and that therefore a rapidly spinning black hole is a necessary condition for jet production. However, it is not a sufficient condition and there must be other parameters that come into the equation.

4.2. *Accretion Rate*

The sensitivity of jet production on the accretion rate seen in Galactic black holes seems to also be reflected in AGN data: assuming a constant R dividing line, a larger fraction of AGN are radio-loud at low accretion rates than at higher ones.^{19,20,22} Yet, while jet formation is quenched in Galactic sources once the accretion rate exceeds $\sim 2\%$ of the Eddington limit,¹⁰⁴ there are many radio-loud quasars and BLRGs that are counter-examples in the AGN community. Both 4C+74.26 and MCG-6-30-15 have accretion rates greater than this limit.^{78,96} Therefore, since radio-loud AGN may be found over a wide range of accretion rates (relative to the Eddington rate), it seems that this is not a vital parameter in the production of powerful radio jets, although a greater fraction of the accretion energy may be directed into radio structures at low accretion rates.

4.3. *Accretion Physics*

Theoretical studies of jet formation from accreting black holes have emphasized the importance of the poloidal component of the magnetic field at the inner edge of the accretion flow in providing conditions appropriate to jet launching and collimation.^{105,106,107} A simple way to enhance this component of the magnetic field is to increase the value of H/r of the accretion flow, where H is the disk scale height and r is the radius along the disk. The importance of H/r in extracting energy from a spinning black hole and launching a jet is now being observed in the latest numerical simulations.⁸⁶

Standard radiatively efficient accretion disks are thin with $H/r \ll 1$.¹ However, when the accretion rate is very low compared to Eddington, the flow can transition to a radiatively inefficient phase that, due to its inability to cool, will have $H/r \sim 1$. Such accretion flows are expected to exist within low-luminosity AGN and Galactic black holes in their low/hard states and can then help explain the presence of radio jets in these objects.¹⁰⁶ In this case, all that is required to produce a powerful radio jet would be a rapidly spinning black hole to provide the energy, and a favorable magnetic field geometry to extract this energy and provide collimation.

We are left then with the problem of radio-loud quasars and BLRGs that will have rapidly spinning black holes, but will be accreting at too high a rate to support a radiatively inefficient accretion flow. At these large accretion rates, the disk may develop a radiation pressure dominated region close to the black hole that will increase H/r .¹ However, both 4C+74.26 and MCG-6-30-15 will have such radiation pressure dominated regions in their accretion disks, but only 4C+74.26 is successful in producing a large-scale jet.

4.4. *Black Hole Mass*

Although the value of the black hole mass is not important for jet formation by Galactic black holes, it does seem relevant for AGN (see right-hand panel of Fig. 1).

Specifically, the black hole masses at the center of radio-loud AGN are almost always $> 10^8 M_\odot$. Radio-quiet AGN can of course also harbor such massive black holes, but radio-loudness is practically confined to this range of masses. This holds true for our two test cases: the radio-quiet MCG-6-30-15 has a black hole mass $\sim 4 \times 10^6 M_\odot$, while the black hole in the BLRG 4C+74.26 is estimated to be $1000\times$ larger.³³

Clearly, radio-loud AGN do prefer to reside in galaxies that have undergone a major merger and will therefore harbor the most massive black holes.^{38,39} These black holes will most likely have a very large value of a , but as discussed in § 4.1, this is not the key parameter in jet formation. Therefore, the question still remains: why does the energy flow at the center of the accretion disk care about the black hole mass? Studies of X-ray variability from both Galactic black holes and AGN show that, as best as can be determined, accretion physics is scale free.¹⁰⁸ As the black hole mass determines only the size scale of the accretion system, it should not be important to the underlying physics. Moreover, what determines this almost magical dividing line of $\sim 10^8 M_\odot$? Is it a selection effect, or evidence of the key to jet formation?

According to simple analytical accretion disk models, H/r is virtually independent of the central black hole mass,¹ but radiation pressure dominated regions are well known to be unstable in a variety of different ways.^{109,110,111,112,113} Simulations of jet formation from radiation pressure dominated disks have yet to be performed. Perhaps it is possible that the rapid instabilities in these type of flows discourage jet formation in lower mass black holes. Alternatively, theoretical models of jet formation have argued that the total jet power produced is dependent on the black hole mass.¹⁰⁶ Such a dependence has been claimed in recent studies of certain AGN samples.¹¹⁴ In this scenario, the total power available to the jet is much larger in 4C+74.26 than in MCG-6-30-15, allowing the jet from 4C+74.26 to break out of the host galaxy and become visible in the low-density intra-galactic medium. More work is clearly needed to elucidate the connection between black hole mass and jet formation.

5. Conclusions

Uncovering the mechanisms underlying the production of powerful and collimated radio jets is a very interesting problem. Jets appear in only a small fraction of AGN, yet they are a nearly universal phenomenon, as they appear in all relativistic accreting systems down to neutron stars. The physics behind this process must at the same time be highly scale free and adaptable, yet simultaneously be complex enough in order for jets from AGN to be relatively rare. While a complete understanding of the processes involved is still lacking, enormous observational progress over all wavelengths has allowed a narrowing in on the key parameters.

X-ray spectroscopic measurements of the Fe $K\alpha$ line and reflection features probes the accretion disk geometry in AGN. There now exists tentative detections of relativistically broadened Fe $K\alpha$ lines from three BLRGs: 3C 120, 4C+74.26

and PG 1425+267. These three examples indicate that these radio-loud AGN have optically-thick, radiative efficient accretion disks down to small distances from the black hole, similar to the radio-quiet AGN. It is of paramount importance that further deep X-ray observations be undertaken to confirm these detections and expand the sample of known Fe K α lines. In contrast, most radio-loud AGN have such low luminosities that they will likely harbor geometrically thick, radiatively inefficient accretion flows. Additional observations and modeling are also needed to confirm this conclusion.

Combining the multiwavelength data with the results of numerical studies, we conclude that there are three necessary conditions that must all be satisfied for the production of a powerful radio jet: a rapidly spinning black hole (provides the energy source), an inner accretion flow with a large H/r (provides the enhanced poloidal magnetic field and collimating mechanism) and a favorable magnetic field geometry. This last condition is still amorphous, but seems to be required in order to explain the significant fraction of low-luminosity radio-quiet AGN. Depending on its individual history, a rapidly spinning black hole may exist in any galaxy, but seems most likely to reside in a massive galaxy that has undergone at least one major merger. An accretion flow with a large H/r is naturally predicted by models of radiative inefficient accretion flows, but may also be provided by the radiation pressure dominated region of a standard Shakura-Sunyaev disk. The black hole mass seems to play an important role in the formation of jets in radio-loud AGN, perhaps through increasing the total power output in the jet.

The evident complexity of this process means that several reasons are possible to explain why radio-quiet AGN lack a powerful jet. In the case of radio-quiet Seyfert galaxies that reside in disk galaxies, the reason may be a lack of a rapidly spinning black hole. In the case of MCG-6-30-15, the reason may be that the relatively small black hole mass does not generate enough jet power. The lack of a suitable magnetic configuration may explain the radio-quiet quasars. These conditions can be isolated only by a careful comparison of radio-loud and radio-quiet AGN at a number of different accretion rates. Finally, X-ray spectroscopy is currently the only direct observational technique available to measure black hole spins. Thus, long X-ray observations are crucial for understanding the accretion geometry of radio-loud active galaxies.

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14 *D.R. Ballantyne*

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